Historical Brief

GL Atmospheric Propagation Codes

For DoD Systems

PHILLIPS LABORATORY

HANSCOM AFB, MA 01731-5000

Historical Brief

GL Atmospheric Propagation Codes

For DoD Systems

GL Atmospheric Propagation Codes for DoD Systems

(Revised Edition)

Ruth P. Liebowitz

GL Historian

May 1990

EXECUTIVE SUMMARY

The Geophysics Laboratory (AFSC) has developed a set of atmospheric propagation codes for Department of Defense (DoD) systems. The LOWTRAN (Low Spectral Resolution Transmission) Code is used for all systems for which low-resolution transmission is adequate (e.g., imaging systems). FASCODE (Fast Atmospheric Signature Code) is applied to those requiring high-resolution transmission (e.g., laser systems). By calculating the effects of atmospheric transmittance/radiance on optical/infrared systems, LOWTRAN and FASCODE considerably enhance both the design of DoD systems and their operational performance. In 1978 the two codes, together with the supporting HITRAN data base, were declared the standard propagation models for DoD agencies by the Undersecretary of Defense for Research and Engineering (OUSDRE).

The codes are currently in use with a wide variety of tactical and strategic systems. In the tactical arena, they are indispensable to evaluate the performance of electro/optical systems for "smart weapons," such as the Imaging Infrared (IIR) Maverick and the PAVE TACK System. In the strategic arena, they support the operation of infrared detection and surveillance systems and of ground-based laser weapons being developed for the Strategic Defense Initiative (SDI). Responding to the 1978 directive from OUSDRE, GL continues to update and expand its propagation codes. The new moderate resolution (MODTRAN) transmission code completed in 1989 responds to anticipated requirements for aerial reconnaissance and targeting.

TABLE OF CONTENTS

Introduction 1

The Creation of LOWTRAN and FASCODE 4

Impetus for Code Development 8

Recent Code Improvements 12

Current Military Applications 20

Conclusion 29

Acknowledgement 31

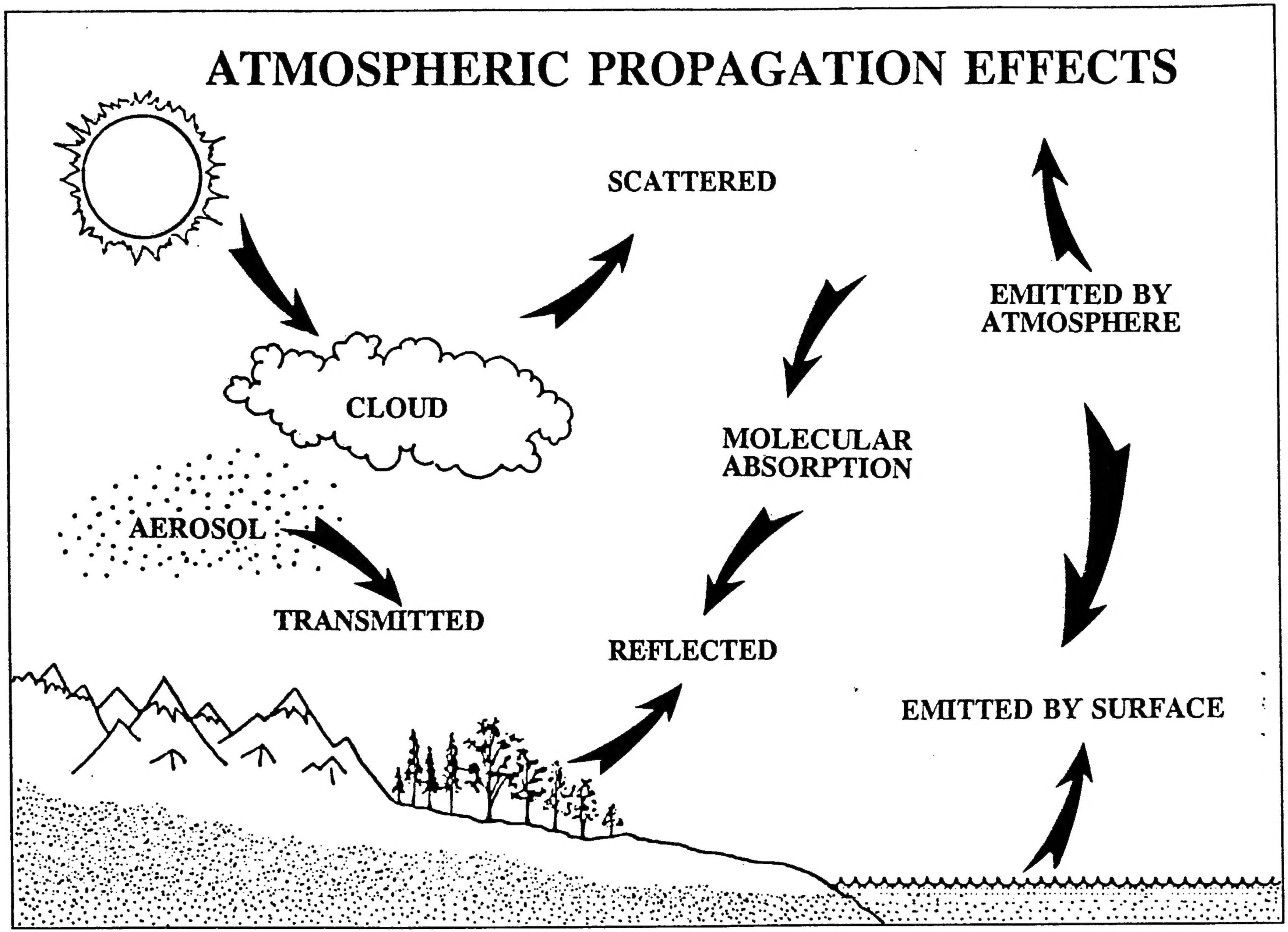
Appendix: List of Laser, TV and IR Electro-optical Systems
Supported by TDAs 33

ATMOSPHERIC PROPAGATION CODES FOR DOD SYSTEMS

Introduction

Most DoD detection and weapons systems have to look through the atmosphere to see their targets, which appear against a background of earth, sky or space. However, the atmosphere does not present a transparent medium for the operation of DoD systems. Molecules and larger particles in the atmosphere may absorb, scatter, attenuate or extinguish beams from optical and infrared systems, while background radiance (solar and thermal) may mask the targets being viewed. Transmittance/radiance phenomena have varying effects on DoD systems. These effects depend on the wavelengths at which a particular system operates, the length of its path through the atmosphere, and the geometry (the slant and altitude) of the path. To deal with these complex phenomena, the Geophysics Laboratory (AFSC) has developed Atmospheric Propagation Codes which predict transmittance/radiance effects for DoD systems propagating under these varying conditions.

The Laboratory has provided DoD with two major propagation codes, LOWTRAN and FASCODE. LOWTRAN (Low Spectral Resolution Transmission) is a one-parameter, band-model code which predicts transmittance/radiance for systems requiring low spectral resolution (20 cm^{-1}). These predictions use algorithms developed at GL to calculate the average transmittance value for a given atmospheric path. The latest version of the code (LOWTRAN 7) has a spectral range which spans from the near-ultraviolet through the microwave region. One of the code's major advantages is its fast computational capability, which makes it suitable for operational use. The modular structure of the code, designed for


ATMOSPHERIC PROPAGATION EFFECTS
SCATTERED
EMITTED BY
ATMOSPHERE
CLOUD
MOLECULAR
ABSORPTION
AEROSOL
TRANSMITTED
REFLECTED
EMITTED BY SURFACE

flexibility, includes options for gaseous or molecular profiles and for larger particles in the atmosphere. The latter includes atmospheric aerosols (dust, haze, smoke) and hydrometeors (fog, clouds, and rain). Because of limitations in the molecular band-model approximation used in the code, LOWTRAN does not apply to upper atmospheric regions (above about 40 km). LOWTRAN is used primarily as an aid for tactical systems operating in the lower atmosphere or on the earth's surface. It applies to the classical scenarios for conventional warfare: air strikes, air-to-air missions, and close air support for ground-launched weapons.

The second major code is FASCODE (Fast Atmospheric Signature Code). It models calculations of the absorption line shapes for individual atmospheric emitters using algorithms created by GL scientists. Spectral line data for its line-by-line calculations are contained in the HITRAN (high-transmission) data base, which has been compiled at GL. Because FASCODE is a physically exact code, it achieves a much higher level of accuracy than LOWTRAN. However, the computer time required to do the complex line-by-line calculations makes it computationally much slower than LOWTRAN. The application for FASCODE is for all systems requiring predictions for high-resolution propagation. These typically would be either laser or strategic infrared detection systems, but the code works equally well in the ultraviolet, visible, and microwave regions. Supporting both codes is GL's computerized HITRAN (high-transmission) data base, which contains the spectral line data for deriving parameters used in band models.

In 1978 both the LOWTRAN and FASCODE codes, together with the supporting HITRAN data base, were declared the standard transmission models for DoD agencies by the Undersecretary of Defense for Research and Engineering (OUSDRE). At the same time, the Laboratory was given the responsibility to maintain and update the models and to communicate improvements made in them

to other agencies. The main vehicle of communication to military users is the Annual Tri-Service Review Conference on Atmospheric Models, which GL has held each year at Hanscom Air Force Base since 1978. Scientists have also conducted an annual workshop at Wright-Patterson Air Force Base every year since 1977, in order to accommodate the large community of code users there. A new workshop was started for users at Kirtland Air Force Base, NM, early in 1990.

The Creation of LOWTRAN and FASCODE

GL's current role as official keeper of the codes rests on a much longer history of scientific investigation and technical innovation in the field of optical/infrared physics. The Laboratory's predecessor organization in the 1950s, the Air Force Cambridge Research Center (AFCRC), gathered together a core of expertise in molecular spectroscopy and thermal radiation effects. The personnel included John N. Howard, one of the team (Howard, Burch and Williams) who, in the early 1950s, pioneered quantitative measurements of transmission using long cells. In the 1960s, the new Optical Physics Division at AFCRC, (renamed the Air Force Cambridge Research Laboratories (AFCRL) as of 1960), sponsored an extensive program of basic research in infrared spectroscopy through contracts with universities. In-house work at AFCRL during this decade pioneered the development of Fourier spectroscopy and contributed to studies of ozone and molecular theory.

During the 1960s, AFCRL began to work towards the creation of transmission models. The enormous amount of time then required to do line-by-line calculations manually discouraged the creation of high-resolution spectral models. In response to this difficulty, the early 1960s had seen the creation of band-models such as the Goody and Altschuler models to achieve predictions for

low-resolution transmission. While the accuracy of their predictions was approximate, the algorithms used permitted them to be made with sufficient speed to have a workable tool. In the late 1960s, the Director of the Optical Physics Division, John Garing, sponsored a new transmission modeling effort, which was headed by Robert A. McClatchey. It included programs both to improve band-models and to move towards a high-resolution model. In the first area, scientists created an improved version of the Altschuler models to achieve more reliable predictions. The result was an AFCRL report entitled Optical Properties of the Atmosphere which appeared in 1970. Drawing on recent laboratory transmittance measurements complemented by available theoretical molecular line constants in line-by-line transmittance calculations, it presented in a graphical form an empirical prediction scheme for low-resolution transmittance. The growing availability of computers in the early 1970s suggested them as a more flexible format for making calculations. In 1972, John E.A. Selby and Robert A. McClatchey converted the material previously reported in graphical form into the computer model LOWTRAN 2.

In the development of LOWTRAN, the initial stimulus had come from scientific efforts to improve understanding of the atmosphere. As the 1960s progressed, the military applications of the work came more to the foreground. Precision-guided munitions (PGMs) with electro-optical systems, popularly called "smart weapons," were being developed in order to achieve "night vision" for reconnaissance and operations in Vietnam. Their deployment raised the issue of transmission in the annual weather cycle of Southeast Asia. In the early autumn of 1968 (monsoon season) and early spring of 1969 (dry season), AFCRL's C-130 aircraft conducted support missions in Thailand to acquire a Southeast Asian data base for evaluating low light level TV systems. This campaign was part of the Air

Force's broad SHED LIGHT Program. During the 1970s, the new LOWTRAN code became a tool in the further development of electro-optical systems. In particular, it was used to predict the performance of forward-looking infrared systems (FLIRs).

Parallel to this applied effort, AFCRL continued to pursue basic research goals. The infrared spectroscopy programs of the 1960s had created a wealth of new material on the frequencies, intensities, and the vibrational, rotational, and collisional energy levels of molecules. In the late 1960s, John Garing organized an interagency Group on Atmospheric Transmission, the so-called GOAT Committee, headed by Robert A. McClatchey, to make a systematic compilation of spectral line data as the basis for creating a high-resolution transmission model in the future. One of the key participants in the GOAT Committee was W.S. Benedict, then at the University of Maryland. The end product of its work in 1973 was the first edition of the HITRAN data base, which was then called the AFCRL Atmospheric Absorption Line Parameters Compilation. It covered the seven major atmospheric absorbers in the infrared (carbon dioxide, water vapor, ozone, nitrous oxide, carbon monoxide, methane and oxygen). The new Compilation became a basic resource for all ongoing efforts to improve transmission models.

In the 1970s, AFCRL scientists took up the major challenge of creating a high-resolution transmission code. For high spectral resolution, the line-shape of molecular absorption is as relevant as frequencies and intensities, and collision-induced radiation is also a major factor. The expansion of computer capability around the turn of the 1970s made the project of calculating individual line-shapes less formidable than before. The first Laboratory effort to model line-shape data was the original HITRAN computer program, which was published with the first edition of the Line Parameters Compilation in 1973. While HITRAN achieved

resolutions of orders of magnitude above the just-published LOWTRAN 2 code, it was very cumbersome and slow in its operation.

In the mid 1970s, scientists at AFCRL (soon to become AFGL) focused their efforts on developing algorithms to speed up line-by-line calculations, and they achieved two major breakthroughs. The first and most significant came when Shepard A. Clough and Frank X. Kneizys devised the HIRRAC algorithm, which was first published in 1977. It proposed a method of decomposing a line-shape into subfunctions in order to minimize the number of samples needed to calculate the line-shape. By considerably reducing the number of samples required, they accordingly lessened the calculation time. The second breakthrough was the development of an algorithm to model the Voigt line-shape. These algorithms formed the core of the first FASCODE package, which appeared in 1978, providing a workable tool to calculate high-resolution spectral transmittance for a multi-layered atmosphere.

The military requirements for FASCODE related to developing laser systems, which had a variety of applications. Already in the early 1970s, while work on the code was just getting underway, AFCRL scientists had calculated transmittances for HF and DF laser systems being developed by the Navy for ship-to-ship ranging. FASCODE itself was used in the late 1970s and early 1980s as a diagnostic tool for experiments performed by the Airborne Laser Laboratory, then under development at the Air Force Weapons Laboratory (AFWL). For high-resolution infrared systems, the new code was used to enhance the performance of satellite surveillance systems that detect missile plumes or aircraft exhaust emissions. Because of its much higher accuracy, agencies started to use FASCODE to validate LOWTRAN predictions for the performance of FLIRs.

The Impetus for Code Development

Since LOWTRAN and FASCODE first appeared in the 1970s, they have been updated several times. LOWTRAN has been issued in 3, 3b, 4, 5, 6 and, most recently, version 7. For FASCODE there have been editions named 1b, 1c, and lastly 2. Similarly, the supporting HITRAN data base has been re-issued several times, the last in 1986. The impetus for the development of the codes has been three-fold. The first is to improve the accuracy of the codes' predictions and to expand their spectral coverage. The second is to respond to changing requirements for DoD systems. A third impetus have been given by the need to keep the computer software and formatting up to date with the latest technology.

To improve the codes' accuracy, GL scientists have worked along two general lines. The first has been to incorporate the latest basic research in atmospheric optics, chemistry, and physics into LOWTRAN, FASCODE, and HITRAN. The second has been to improve the handling of atmospheric properties and meteorological variables which affect transmittance/radiance predictions. In both these areas, the Laboratory has conducted supporting measurement programs whose results can be incorporated into the spectral data base and into models for the codes.

One major ongoing area of work has been to address several specific phenomena which can drive up the error rate on code predictions, namely, aerosols, water vapor, and scattering from background radiances. Aerosols (dust, haze, and smoke) are highly variable in nature and the existing data base on them is limited. Under certain conditions, they can send the error rate for LOWTRAN predictions soaring above the average 5% error rate. By contrast, the calculations for molecular

absorption have been sufficiently refined so that, if the atmospheric path is known, they can now be done reliably and accurately. In each of the updated versions of the codes, better models of aerosols and hydrometeors have gradually been incorporated, but there is still room for much improvement in this area. An effort has also been to achieve a better handling of the water vapor continuum in the codes. Like aerosols, water vapor has a non-uniform mixing ratio and similar effects on code predictions. Another major source of error comes from omitting the effects of single and multiple scattering from background radiances, at lower wavelengths from solar sources, at higher wavelengths from thermal sources.

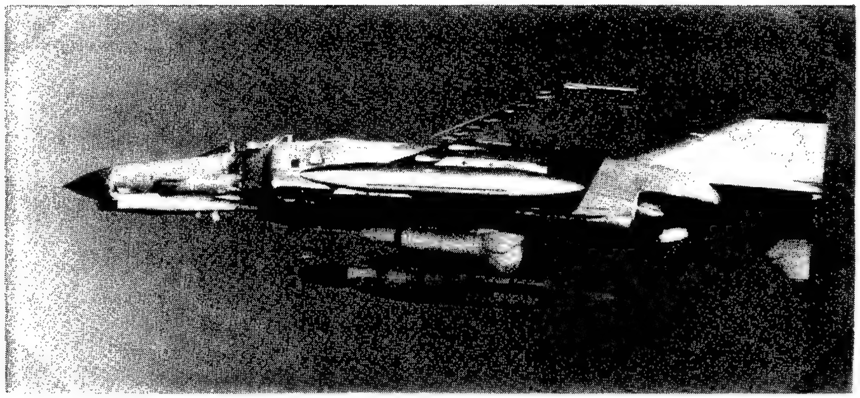
The second major impetus for code development has been increases in DoD requirements and new applications. In general terms, as the sensor systems for weapons improve, this increases the requirements on code predictions for transmittance/radiance. It implies lower error rates, the capability to predict for more complex and longer atmospheric paths, and better spectral and angular resolution. This trend has been apparent both in electro-optical systems for tactical warfare and in laser and infrared/microwave systems for strategic warfare.

In the tactical arena, a new area of requirements opened for the LOWTRAN code in the 1970s. With the winding down of the Vietnam war and the concern about potential conflict between the Eastern and Western blocs in Europe, the focus of attention for transmission applications shifted to Europe. AFCRL's C-130 aircraft made new transmission measurements there in the early 1970s in support of military planning. Experience with testing electro-optical weapons in adverse weather conditions in Europe led to the conclusion that it was necessary to acquire a comprehensive picture of how the local atmosphere affected systems. In response, AFCRL together with seven NATO countries organized and coordinated the OPAQUE (Optical Atmospheric Quantities in Europe)

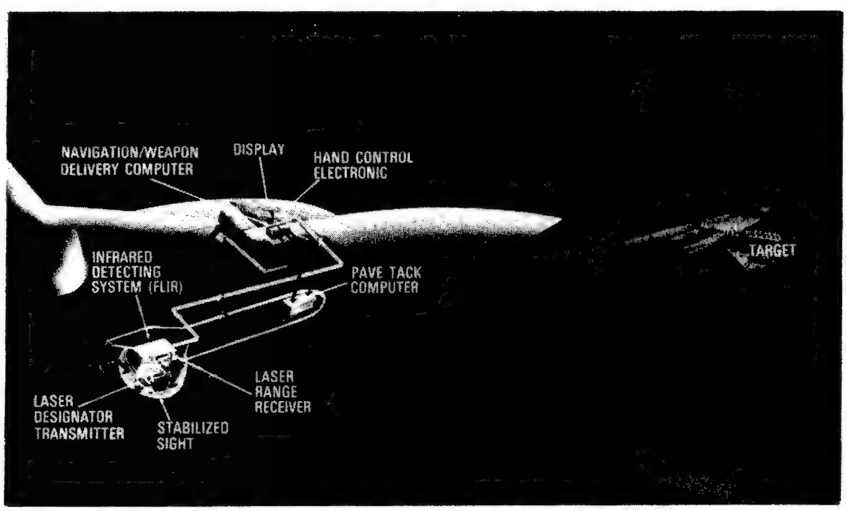
measurements program, which ran for three years from 1976-1979. The OPAQUE program yielded an extensive statistical data base for the climatology of optical/infrared properties in western Europe. It became possible to predict more accurately the percentage of time that a particular electro-optical system would be deployable there during different seasons of the year. Using the data from these field campaigns, GL scientists were able to validate part of the LOWTRAN code and to further develop the aerosol and fog models for it. On-going work on the water vapor continuum also contributed to lowering the error rate for transmission predictions in the European theater.

In the later 1970s, another issue arose in the development of electro-optical systems for tactical use. Tests of the Imaging Infrared (IIR) Maverick were plagued by unexpected reversals of anticipated target/background contrasts. Out of these difficulties emerged the new concept of an integrated set of tools, the Tactical Decision Aid (TDA), to enhance the performance of the electro-optical sensors used with PGMs. The TDAs would first calculate target/background contrast radiance. An atmospheric transmission code would then be used to calculate attenuation of that contrast over various ranges to simulate approach to the target. (LOWTRAN would be appropriate for broadband optical and infrared sensors and FASCODE for laser designator/ranger and receiver systems.) When the degraded contrast exceeded the threshold required for target detection or weapon system lock-on for the particular weapon system, the range prediction was displayed. Using the TDAs in conjunction with short-term weather forecasts, military commanders could compare the predicted maximum acquisition and lock-on range for various PGMs and choose the most appropriate one for an upcoming mission.

Since 1981 GL's Atmospheric Sciences Division has been the central manager of the TDA Program as part of its Advanced Weather Systems Program



A USAF F-4E aircraft in the mid 1980s with the PAVE TACK System (white pod) and a munitions package (dark pod) mounted underneath it.



PAVE TACK Operational Block Diagram

(PE 63707F). The first PGM for which a TDA appeared was the IIR Maverick, whose initial manual version appeared in 1983. After 1983 the TDAs became computerized. Research grade TDAs were run on mainframe computers to optimize primary modeling capabilities, while TDAs which ran on microcomputers became available for use in the field starting in 1985. The research part of the program has been managed for GL by the Avionics Laboratory at Wright-Patterson Air Force Base. One system for which AFGL managed the development of a TDA was PAVE TACK, which has both FLIR sensors and a laser designator/ranger system. (See the illustration, page 11.) In 1986 the TDA for the PAVE TACK FLIR proved very effective in the US strike against Libya.

In the strategic arena, upgraded versions of FASCODE supported satellite surveillance missions. Improvements in satellite detector technology enabled agencies to have more choice of wavelengths for these infrared systems, and FASCODE was used by systems designers to compare transmittance/radiance effects for candidate wavelengths. GL scientists incorporated additional spectral line data into the HITRAN data base in order to improve FASCODE for these applications. In the early 1980s they also conducted studies to start dealing with the scattering problem for laser systems.

Recent Code Improvements

In the last four years, GL has substantially advanced and expanded the atmospheric propagation codes. Groups in several branches of the Optical and Infrared Technology Division have been working on different aspects of the codes and on research directly supporting or relevant to them. A new version of LOWTRAN, LOWTRAN 7, was issued early in 1988 and a new version of FASCODE, FASCOD3, is nearing completion. The LOWTRAN code had reached

such a mature stage of development and broad usage that, later in 1988, the new LOWTRAN 7 was transferred to industry for commercial reproduction. GL also sponsored the creation of a new moderate transmission (MODTRAN) code, which first appeared in 1989. In support of the codes, scientists have prepared several new or improved models for aerosols and particulates. Further improvements have also been made in GL's HITRAN data base, based in part on research conducted by the Laboratory.

The LOWTRAN 7 version was completed early in 1988 and released publicly in February 1989. It expanded the spectral coverage of its predecessor LOWTRAN 6 to include the region from the near-ultraviolet through the microwave region. In terms of revised models and other refinements, it represented a significant increase in sophistication over LOWTRAN 6, which had been issued in 1983. Scientists at GL compiled a new atmospheric data base for use with LOWTRAN. It presented six reference atmospheres with varied constituents as a function of altitude, allowing a range of climatological choices, plus separate molecular profiles for 13 minor and trace gases.

To improve the averaging process in LOWTRAN for calculating transmission, separate band models and band model absorption parameters were developed under contract for gases previously characterized as uniformly mixed (CO_2, N_2O, CO, CH_4, O_2), trace gases (SO_2, NO, NO_2, NH_3), water vapor, and ozone in the infrared and microwave. Analytic transmission functions (double-exponential) replaced numerical tables used in previous LOWTRAN models. The new models were developed with and based on degraded line-by-line spectra (from FASCOD2), and they were validated against laboratory measurements.

Absorption coefficients for various "windows" in the LOWTRAN range were specially calculated to improve accuracy. These included absorption values for

the water vapor continuum at 10 microns, which were adjusted from those used in LOWTRAN 6. For the ultraviolet wavelengths, new absorption parameters for molecular oxygen (Schumann-Runge bands, Herzberg continuum) were added to the code, and the absorption data for ozone were updated. There were major improvements in the characterization of background radiance in LOWTRAN 7. An improved extra-terrestrial solar source function was included, and the single scattered solar and lunar radiance model of LOWTRAN 6 was augmented by an efficient and accurate multiple scattering parameterization.

All the existing aerosol models and the rain model in the previous LOWTRAN 6 were extended through the millimeter wavelength region. Water cloud models from FASCOD2 were added, and two new cirrus cloud models were developed for LOWTRAN 7. A new aerosol model with a wind speed dependence for desert conditions was also developed. Improved models for background stratospheric aerosols were made available.

All these parts added up to an impressive new version of the code. It was accomplished through the coordinated efforts of an in-house team headed by Francis X. Kneizys, and consisting of Eric P. Shettle, Leonard W. Abreu, James H. Chetwynd, and Gail P. Anderson, together with three former GL staff members, William O. Gallery, John E.A. Selby, and Shepard A. Clough. They were supported by contract work (OptiMetrics, Inc., Atmospheric Environmental Research (AER), Inc., and the University of Texas at El Paso) on several of the models and by research across a wide scientific community in America, Canada, Europe, Israel and the Far East. As of November 1989, DoD agencies and contractors, NASA, and organizations around the world made up a group of several hundred LOWTRAN 7 users.

In 1988 the Laboratory negotiated a Cooperative Research and Development Agreement (CRDA) with a local firm, ONTAR Inc. of Brookline, MA, to develop a personal computer version of LOWTRAN 7 for commercial distribution. (This type of agreement was an opportunity provided by the Federal Technology Transfer Act of 1986 to speed transfer of technology to the private sector, and GL was one of the first DoD Laboratories to take advantage of it.) In return for paying GL a fee to cover the Laboratory's costs for validation, improving the input architecture, testing, and debugging the new PC LOWTRAN 7 software, plus providing free copies of it to GL, ONTAR acquired the right to market it. Since the LOWTRAN group at the Laboratory had been planning to develop a desk-top computer version of LOWTRAN 7 itself, this arrangement freed resources for other R&D efforts. The agreement for the CRDA was approved on 1 September 1988 by Colonel J.R. Johnson, Commander of the Air Force Space Technology Center. As of 1 May 1989, GL scientists had completed an accuracy check of the new ONTAR version, and the Laboratory-endorsed product was ready for marketing.

In fiscal year 1989, GL scientists were in the final stages of preparing the newest version of the high-resolution transmission code, FASCOD3, for distribution later in 1990. As some indication of the complexity of its line-by-line calculations, currently FASCODE numbers 40,000 lines of computer code compared to LOWTRAN's 18,000 lines. Like its predecessor FASCOD2, which was published in 1986, FASCOD3 can be applied to spectral regions from the microwave to the middle ultraviolet, and it relies on an external line atlas, such as HITRAN, for standard spectroscopic parameters. FASCOD3 added some new capabilities. These included consistent line-coupling options to handle the effects of closely-spaced spectral lines, and an improved NLTE (non-local thermodynamic equilibrium) capability for line-of-sight paths involving the atmosphere above 60 km. FASCOD3

users will also have access to the new features which appeared in LOWTRAN 7: the thermal multiple scattering option, extension of the UV diffuse absorption, the atmospheric data base, and the aerosol, rain, and cloud models.

The staff at GL working on FASCOD3 overlaps considerably with the group named above for LOWTRAN. The lead scientist for FASCODE had been Shepard A. Clough, now at Atmospheric and Environmental Research, Inc. (AER). Currently Gail P. Anderson has assumed this position. Because of its technical complexity, FASCODE developed at a slower pace, and it has not yet approached the ubiquity of LOWTRAN. At present its users number just under 200. FASCODE's reputation as a standard for line-by-line calculations within the scientific community was enhanced by the 1986 Intercomparison of Transmittance and Radiance Algorithms (ITRA) Conference. Here the general FASCODE algorithm was demonstrated for use in satellite measurements of nadir, limb, and microwave transmittance/radiances. As a result of the ITRA Conference, the weighting functions in FASCODE representative for typical satellite measurements for remote sensing were made more efficient. FASCODE continues to serve as a validation tool for more pragmatic band model development.

There are three external line atlases available to FASCODE. The main one has been the GL HITRAN data base. The latest edition of 1986 combined the growing data base on molecular absorption of infrared emitters with a trace gas compilation first published in 1982. Current work on HITRAN, carried on by Laurence S. Rothman, is aimed toward publishing a new version of HITRAN in the latter part of 1990. It will include new data for the visible and near infrared regions for water vapor, vastly improved intensities for CO_2, additional cross-sections for the chlorofluorocarbons, updated ozone bands, plus user-friendly software.

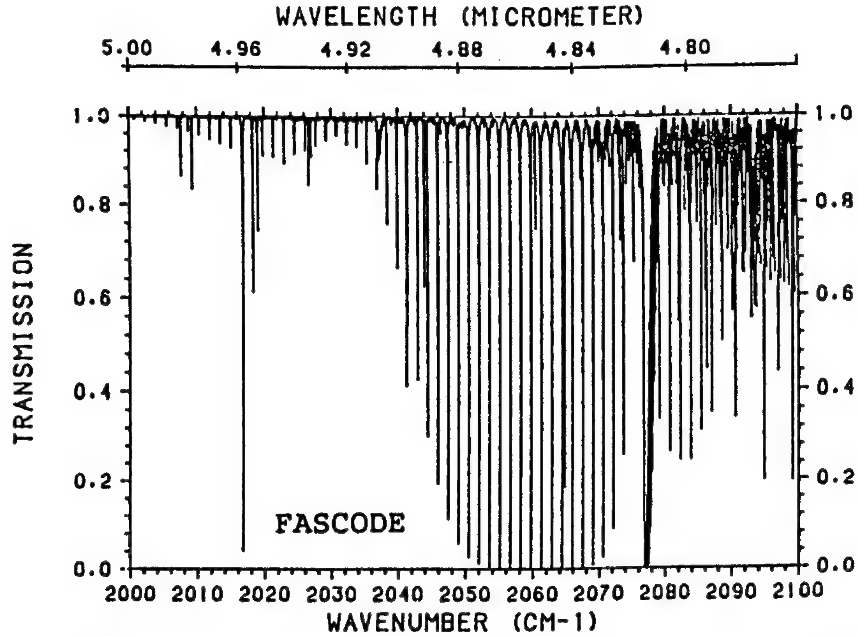
GL has continued to conduct both laboratory and field research programs that support the development of HITRAN and FASCODE. Laboratory programs contribute data on excited states for a new "hot gas" compilation (HITEMP) to supplement HITRAN. In the field, the Stratospheric Cryogenic Infrared Balloon Experiment (SCRIBE) has been flown several times during the 1980s to obtain data on previously unrecorded minor infrared emitters and on the characteristics of different transmission paths. The latest SCRIBE flight in May 1989 obtained some excellent new data.

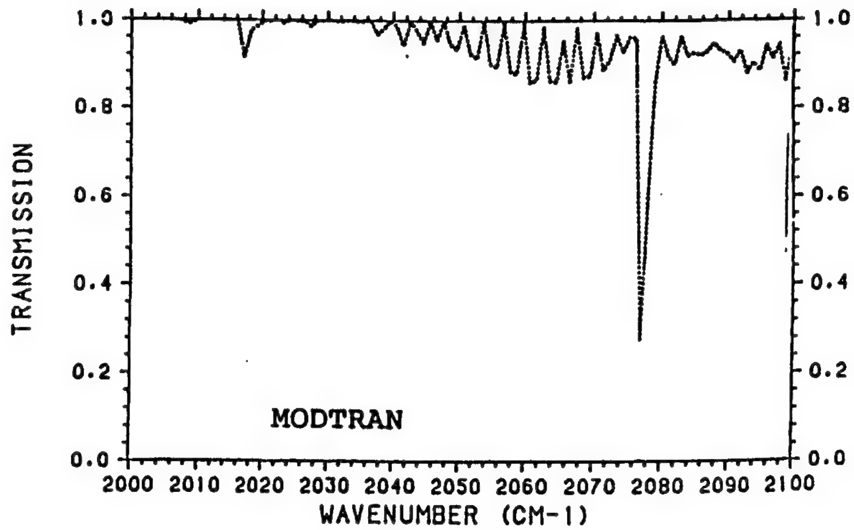
Other external line files can be utilized by FASCOD3. For example, for calculations of infrared transmission in the upper atmosphere where local thermodynamic equilibrium (LTE) breaks down, FASCODE relies on auxiliary hot band O_3 line parameters with their associated NLTE populations. These are simulated by specifying vibrational temperature profiles for each excited state (Degges and D'Agati). The improved NLTE capability in FASCOD3 enables a smooth transition along line-of-sight paths including both LTE and non-LTE contributions.

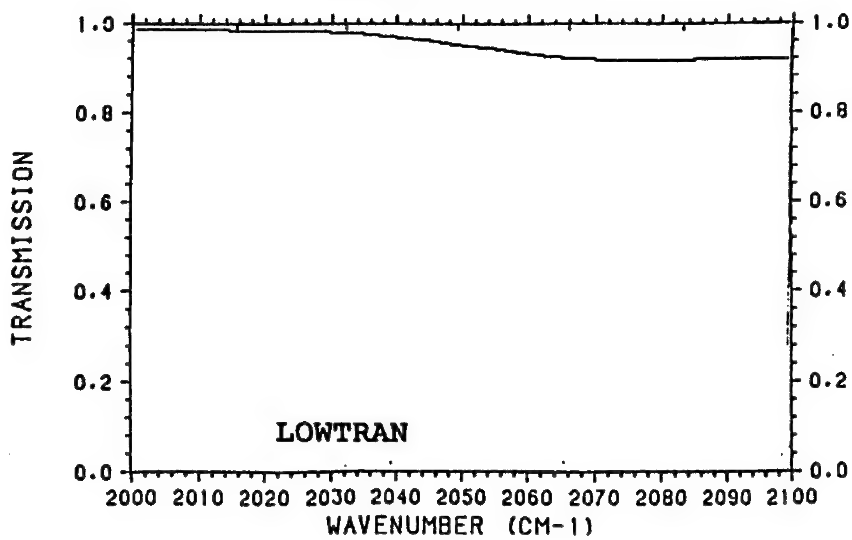
The Degges band model code, officially titled the AFGL/Visidyne High Altitude Infrared Radiance Model (HAIRM), was developed starting in the 1960s as part of a separate set of programs in the Optical and Infrared Technology Division. They were aimed at creating radiance codes specifically tailored for infrared transmission along tangent paths through the upper atmosphere (above 60 km), i.e., under LTE conditions. During the 1980s, scientists have been working to build up line-by-line research models for this type of non-LTE transmission. A non-LTE line-by-line radiation transport code dubbed NLTE, for calculating radiation from non-LTE populations into the line-of-sight of a sensor, was issued in 1983 and updated in 1985.

Currently, efforts are focusing on applying a new code known as RAD which calculates in a line-by-line fashion the radiative contribution to non-LTE populations. RAD is being used to develop new vibrational temperature profiles to validate and/or replace the Degges band-model profiles currently used in FASCODE. Together, RAD and NLTE constitute the research code ARC (Atmospheric Radiance Code). An auroral version of ARC known as AARC (Auroral ARC) already appeared in 1987. These research models have influenced the development of a new code for strategic and SDI applications to succeed the HAIRM code. The first version of the Strategic High Altitude Radiance Code (SHARC-1), which appeared in 1989, is an equivalent band-model code that achieves a spectral resolution of .5 cm^{-1} and is relatively fast running. This group of new codes can be expected to interact with the non-LTE capability in FASCOD3.

In addition to advancing LOWTRAN and FASCODE during the last three years, GL sponsored the creation of the new MODTRAN code. It was completed by Spectral Sciences, Inc. (SSI) under contract in 1989 and released as a beta-test version for DoD use. Currently it is being validated at GL with plans for public release in late 1990. The MODTRAN code is a two-parameter, band-model code covering the same spectral range as LOWTRAN and including all its capabilities. Like LOWTRAN 7, it includes separate band model parameters for a set of twelve molecules but they are calculated at a higher resolution. The new code achieves ten times the resolution of LOWTRAN (increased from 20 cm^{-1} to 2 cm^{-1}), but it requires somewhat more computer time. In contrast to FASCODE, it includes its own spectral data base. With the inclusion of both direct and scattered solar radiances, it is appropriate for middle atmospheric paths (between 30 to 60 km). MODTRAN can also model bands which are in LTE for paths above 60 km, and, in this area, its predictions agree well with SHARC and FASCODE3.


WAVELENGTH (MICROMETER)
5.00 4.96 4.92 4.88 4.84 4.80
TRANSMISSION
1.0 0.8 0.6 0.4 0.2 0.0
FASCODE
2000 2010 2020 2030 2040 2050 2060 2070 2080 2090 2100
WAVENUMBER (CM-1)

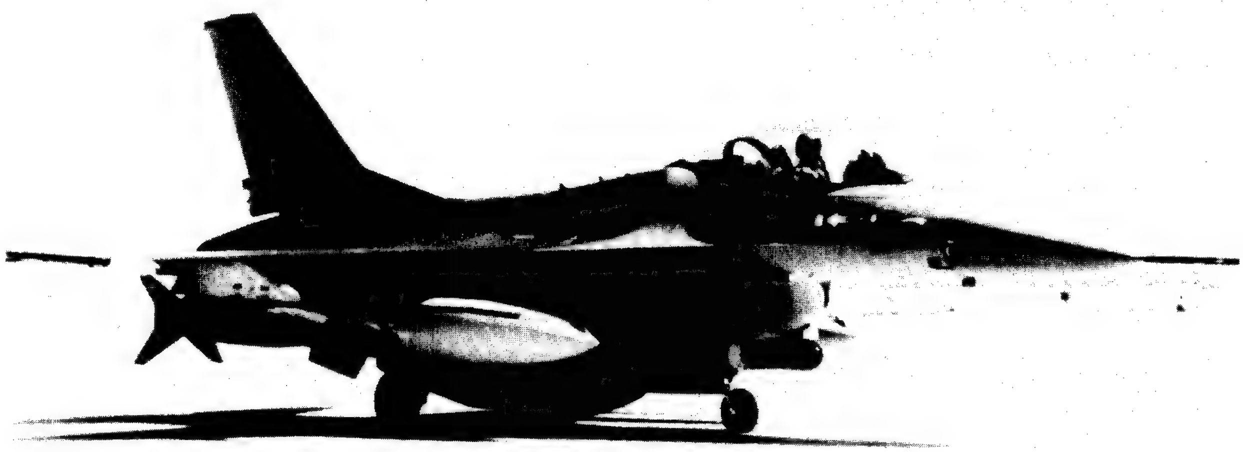

TRANSMISSION
1.0 0.8 0.6 0.4 0.2 0.0
MODTRAN
2000 2010 2020 2030 2040 2050 2060 2070 2080 2090 2100
WAVENUMBER (CM-1)


TRANSMISSION
1.0 0.8 0.6 0.4 0.2 0.0
LOWTRAN
2000 2010 2020 2030 2040 2050 2060 2070 2080 2090 2100
WAVENUMBER (CM-1)

The relative abilities of FASCODE, MODTRAN, and LOWTRAN to detect molecular absorption are shown in this example of a moderately-long, vertical transmission path (10-20 km). (See the illustration on page 19.) With LOWTRAN, much of the spectral definition is traded for speed of operation. MODTRAN gives a rough outline of the spectral shape, while FASCODE presents an exact picture of the different overlapping bands. In terms of resolution, for LOWTRAN the resolution in wave numbers is 20 cm^{-1}; for MODTRAN it is 2 cm^{-1}. The FASCODE resolution is monochromatic or infinite, that is, a true resolution of the radiation being measured.

Current Military Applications

The expansion of the codes over the last four years has responded to a number of DoD requirements, some ongoing and some new. There are the ongoing requirements for LOWTRAN and FASCODE to support PGMs in the tactical arena. The development of LOWTRAN for military applications has continued to be geared primarily to the European theatre, but the addition of desert aerosols to LOWTRAN 7 reflects increased attention to the Middle East. Upgrades of the codes have continued to be incorporated into TDAs, and they in turn are being upgraded and expanded. Model upgrades of the TDAs for the field were released in 1987 and 1989. The latest version (the Mark III Version 1.0) displays acquisition and lock-on ranges for the time over target as a function of attack heading. This, combined with other information about the target area, such as geography and enemy defense positions, permits the aircrew to plan an approach that takes advantage of the longest possible stand-off range. The number of laser, TV, and infrared electro--optical systems supported by TDAs has also expanded considerably.



A USAF F-16A aircraft equipped with a variety of electro-optical and munitions pods. Under the wing, on the far left, an MK84 Laser Guided Bomb. On the right, the laser designator for the MK84 LGB (rounded black tip).

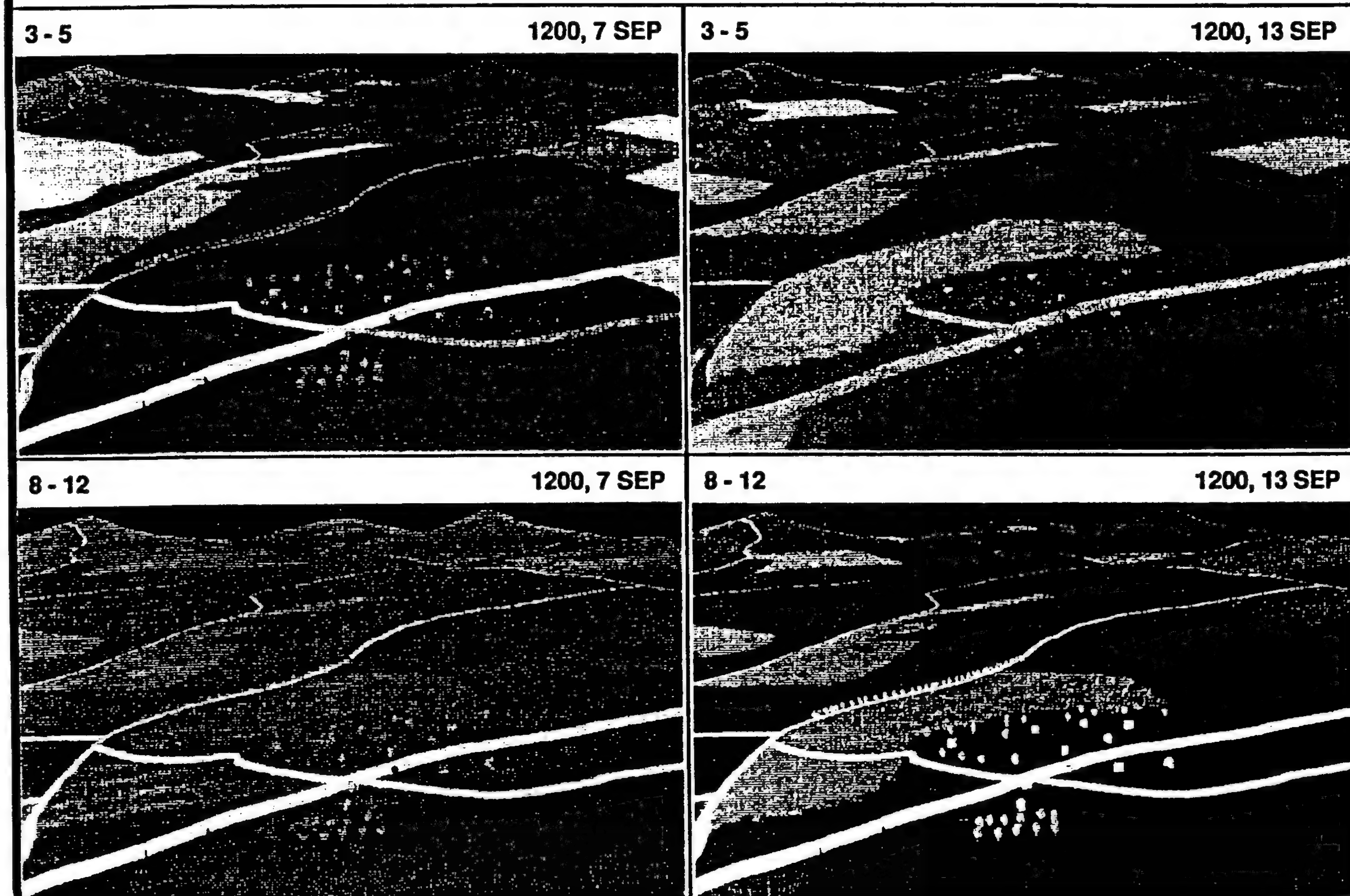
(A list is given in the Appendix.) For a current operational configuration, see the illustration, page 21.

Because there are no fixed relationships for target/background contrast radiances at infrared wavelengths, TDAs for infrared electro-optical systems have continued to present a challenge for reliability in operational use. The original Thermal Contrast Model (TCM I) for the infrared TDA was an empirically-derived model, and scenes for the TDA had to be established on a trial-and-error basis. Since TCM I averaged the heat value of the various facets of its targets, there were difficulties in targeting "hot spots" such as the engine of a moving tank. Also, the model could not support air interdiction of complex, high-value targets, a Tactical Air Force (TAC) requirement. Consequently, a new Model (TCM II) has been developed for the latest Mark III version. The TCM II is a physically realistic model based on first principles. It models the heat value of individual facets of targets like fuel storage tanks, and it resolves questions about specific targets against specific backgrounds. The goal is to work toward more generic versions of target/background contrast.

The same issue of thermal contrast is addressed in a new program in which GL is participating, the Smart Weapons Operability Enhancement (SWOE), but from a different perspective. Whereas the infrared TDA is aimed for use with operational systems under battlefield conditions, SWOE is geared to assist the designers of future electro-optical systems. The SWOE Program is part of the new, DoD, Balanced Technology Initiative (BTI), and it has emerged with the Army's Cold Regions Research and Engineering Laboratory (CRREL) as the lead sponsor. The objective of the program is to provide the principal hardware developers of "smart weapons" with the simulation tools to evaluate proposed electro-optical sensors in conjunction with realistically-defined backgrounds. It will also support

SMART WEAPONS OPERABILITY ENHANCEMENT

SWOE COMPUTED SCENES, IR, HUNFELD, WEST GERMANY



test and evaluation. For the simulations, computerized "scenes" will be generated with background models derived from well-measured "type" environments (e.g. central European, desert, northern and southern US).

GL's Optical and Infrared Technology Division has responsibility for managing the modeling segment of the SWOE Program. Along with several other agencies, it is developing radiometric models of background features (terrain, clouds, tree canopies, etc.) which are then composed into landscapes. For an example, see the "scenes" of Hunfeld, West Germany, showing an aircraft pilot's view of the landscape on two different days (one hazy and one cloudy) each at two infrared wavelengths, page 23. The final goal is to integrate (rather than superimpose) targets into these scenes, adding features like shadows or thermal changes on target surfaces that derive from atmospheric conditions.

The new MODTRAN code responds to recent developments in aerial reconnaissance and targeting. The Air Force has been interested in developing an Infrared Search and Track (IRST) System, which is intended for long-range detection of aircraft. Anticipated requirements in this area provided the impetus for developing MODTRAN. It includes the higher resolution needed for aircraft plumes, the appropriate atmospheric constituents, and new models for cirrus clouds and solar scattering, all of which are important for this type of path. MODTRAN is being adopted as a replacement for LOWTRAN 7 in future updates of the SPIRITS (Spectral Infrared Imaging of Targets and Scenes) code in use at the Aeronautical Systems Division (ASD).

There is an ongoing requirement for FASCODE and HITRAN to enhance the performance of infrared satellite surveillance systems that detect missile plumes or aircraft exhaust emissions. In addition, the strengthening of the near-ultraviolet region in LOWTRAN has improved it for application to missile plume detection.

Current work at GL on a new "hot gas" compilation for HITRAN will enhance FASCODE's capability for simulating plumes as viewed from space.

The Strategic Defense Initiative announced in 1983 has given rise to some challenging new areas of application for the codes, particularly for very high resolution codes such as FASCODE. In the infrared area, SDI expanded the traditional early warning function for satellite infrared systems into the multiple functions defined in the SATKA (Surveillance, Acquisition, Tracking and Kill Assessment) missions. All these functions call for calculations of transmittance/radiance effects at a very high spectral resolution and over very long tangent paths. The radiance of the atmospheric infrared backgrounds against which ballistic targets are viewed must be defined with equally high resolution. GL's work on its high-altitude radiance codes (AARC and SHARC), the NLTE function for FASCOD3, the expansion of HITRAN, and its laboratory, rocket, and Shuttle programs for measuring high-altitude infrared backgrounds all respond to these increased requirements. The SHARC code is specifically intended for the SDI Strategic Scene Generator which, in turn, will become part of the National Test Bed. In a related effort, another group in the Optical and Infrared Technology Division is modeling the zodiacal and galactic infrared background beyond the atmosphere, which also affects the SATKA missions. Its Celestial Background Scene Descriptor will similarly be folded into SDI's Strategic Scene Generator.

In the laser area, the advanced systems proposed for SDI, and also for the ASAT (anti-satellite) program, involve propagation over space-ground or ground-space paths. The characterization of these long, inhomogeneous paths presents significant challenges for predicting transmittance/radiance. They include the identification of atmospheric constituents and larger phenomena (such as sub-visual cirrus clouds) along the paths, and the specification of (and compensation for)

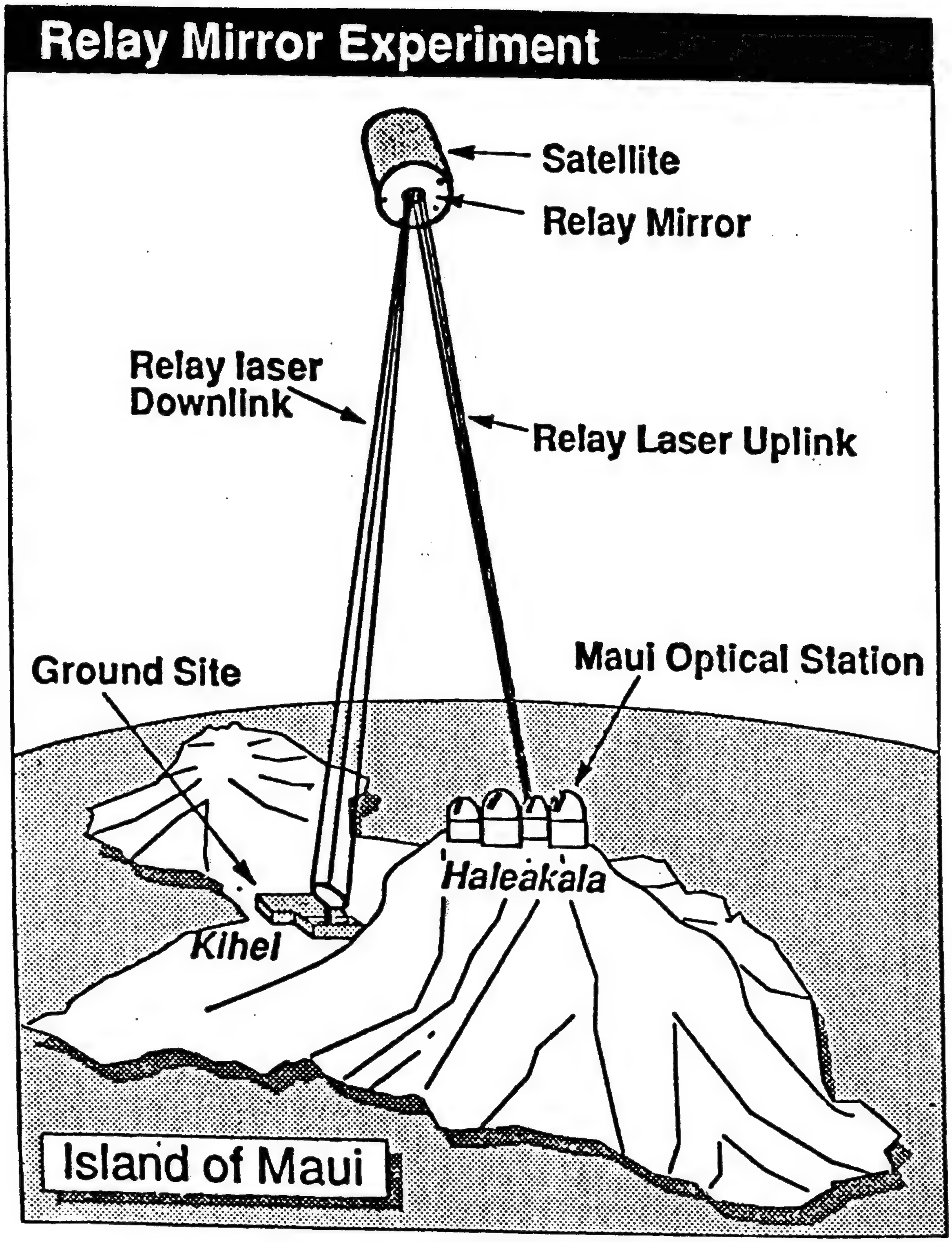
optical turbulence in the atmosphere. There has also been a strong interest among both military and civilian scientific agencies in space-ground paths, with the goal of developing the capability to sense the atmosphere remotely from satellites, particularly in areas for which there is little meteorological data available. A key issue for remote sensing at infrared and microwave wavelengths is the development of techniques for retrieving temperature, pressure, and wind profiles from satellite-measured radiances. For satellite-ground transmission in the microwave region, the Laboratory's Atmospheric Sciences Division has developed the Radiative Transfer Microwave Transmission Code (RADTRAN), which is being used by the Defense Meteorological Satellite Program (DMSP).

In addition to generic difficulties related to their atmospheric path, advanced lasers involve other transmission challenges which are specific to these systems. Ground-based, short-wave, high-energy lasers figure prominently in plans for SDI's Directed Energy Weapons (DEW) mission. As a beam from this type of laser propagates upwards towards space, it interacts with atmospheric gases and aerosols at a number of different levels. In the atmospheric boundary layer (up to several kilometers immediately above the earth's surface), the laser's wave optics encounter the effects of molecular absorption and aerosol extinction. Local heating resulting from absorption acts like a lens in defocusing the laser, causing beam spreading ("blooming") or deflection of the beam from its target. In some circumstances, a beam can break down a gas or vaporize aerosols, creating a cloud which blocks its transmission completely. When the laser's beacon signals to refocus the beam in order to compensate for blooming and other effects, it may give rise to thermal blooming instabilities which interact with the beam's upward path in a non-linear fashion. Problems with non-linear effects are less critical for planned ASAT lasers because they would operate at a significantly lower energy level than SDI lasers.

Optical turbulence in the atmosphere adds to the challenges for laser propagation. By inducing inhomogenities in the refractive index across the beam's wavefront, it reduces the laser beam's coherence and produces scintillations and other irregularities such as beam wander. Turbulence effects can reduce the peak intensity in a ground-space system by a factor of 10,000 if no adaptive optics are used to compensate for these effects. Turbulence also tends to seed thermal blooming instability in the boundary layer.

GL's recent work on its transmission codes has responded to the requirement to clarify these atmospheric issues for proposed SDI systems. Because aerosols contribute significantly to thermal blooming in the boundary layer, the ongoing effort to improve aerosol models in each new LOWTRAN and FASCODE version has made a contribution. The work on refining the characterization of the water vapor continuum in the codes has also been done with an eye to SDI laser requirements. Similarly, the current focus of work on the HITRAN data base, upgrading the quality of data for the visible and near-infrared sections, as well as improving the CO_2 parameters, supports SDI laser applications.

In addition, GL's optical turbulence measurement program, conducted by another group in the Optical and Infrared Technology Division, has provided substantial support to this area of SDI. Close to a decade of field measurements with the GL-developed balloon thermosonde have built up a data base on turbulence and its diurnal, seasonal, and regional variations. Laboratory scientists have provided data on average and "worst case" turbulence to laser system designers working on adaptive optics. GL's profiles of atmospheric turbulence, together with its molecular absorption, aerosol, and water vapor models, have been utilized for the integrated propagation codes designed for specific high-energy laser systems.


Relay Mirror Experiment
Satellite
Relay Mirror
Relay laser Downlink
Relay Laser Uplink
Ground Site
Maui Optical Station
Haleakala
Kihel
Island of Maui

The program has also supported SDI laser test sites, characterizing the turbulence regime above them and participating in actual testing. One site for which GL has provided data and analysis is the Army's free-electron laser (FEL) planned for the White Sands Missile Range, N.M. (GL's meteorologists also measured cloud incidence and distribution for this project.) The Laboratory is currently supporting the SDI Relay Mirror Experiment (RME), which is being conducted by the Weapons Laboratory at the Maui test site in Hawaii. The purpose of the experiment is to test the capability of a satellite mirror to redirect a ground-based laser beam to hit a ground target (see the diagram, page 28). GL will perform accompanying turbulence measurements using its balloon-borne thermosonde.

Conclusion

The Laboratory's atmospheric propagation codes are a set of state-of-the art tools which support a broad range of tactical and strategic systems. They are among the most widely-used of GL's products. LOWTRAN, FASCODE, HITRAN, and now MODTRAN evolved out of approximately thirty years of research and development at AFGL and its predecessor organizations. In the creation of the codes, Laboratory scientists contributed essential analytical techniques, algorithms, and atmospheric models. They also undertook the substantial task of organizing the basic data set on which the codes rest. The results of their work are briefed to US and NATO military agencies, to defense contractors, and to the civilian scientific community.

GL's future code-related work will continue to incorporate upgrades into FASCODE, LOWTRAN, and the new MODTRAN. There are plans to expand the improvements in LOWTRAN 7 for the ultraviolet wavelengths into a new set of

ultraviolet codes. This will be a joint project between the Optical and Infrared Technology and the Ionospheric Physics Divisions. Since the supporting HITRAN data base has become so large, there are plans to change it from a sequential to a relational format using a CD-ROM for ease of operation. In terms of applications, there will be a continued focus on meeting the challenges for remote sensing and for SDI requirements. One specific project is to develop a remote sounding algorithm to be used in conjunction with FASCOD3. The high-altitude radiance codes will have new modules incorporated to improve them for strategic applications. Lastly, funding permitting, the approach through simulations in the new BTI/SWOE program will be pursued for the design of tactical electro-optical systems.

ACKNOWLEDGMENTS

The author would like to acknowledge the technical assistance received in writing this Brief from the following GL staff members:

Francis X. Kneizys, Gail P. Anderson, Leonard W. Abreu, Laurence S. Rothman, Eric P. Shettle, Lt Col George G. Koenig, Richard H. Picard, Robert R. Beland, and John H. Schummers of the Optical and Infrared Technology Division.

Michael J. Kraus, Maj James Hancock, and Vincent J. Falcone of the Atmospheric Sciences Division.

IR Sensor Systems Supported by the Mark III Electro-Optical Tactical Decision Aid (EOTDA)

Sensor Name	Sensor Symbol	Sensor Usage
AC130 FLIR	AN/AAD-7	Air Force
B52 EVS FLIR	AN/AAQ-6	Air Force
IR Maverick	AGM65D, GBU-15	Air Force
IR Pave Tack	AN/AV-Q 26	Air Force
Lantirn Navigation FLIR	AN/AAQ-13	Air Force
Lantirn Targeting Pod	AN/AAQ-14	Air Force
Lana FLIR	AN/AAR-48	National Guard
A-6 FLIR	AN/AAS-33A	Navy
A-7E FLIR	AN/AAR-42	Navy
AV-8 NAV FLIR	AN/AAR-51	Navy
F/A-18 FLIR	AN/AAS-38	Navy
OV-10, P-3 FLIR	AA/AAS-37, AN/AAS-36	Navy
S-3B FLIR	AN/OR-263	Navy
SH-60 FLIR	AN/AAQ-16	Navy
TAS-6A FLIR	AN/TAS-6A	Navy
PNVS		Army
TADS FLIR	AN/ASQ-170	Army

(List current as of January 1990)

TV and Laser Sensor Systems Supported by the Mark III EOTDA

TV

Sensor

AC-130

B-52 EVS

PAVE SPIKE

AN/PVS-5a

AN/PVS-7, 2nd generation

AN/PVS-7, 3rd generation

ANVIS-6

AGM-65A

AGM-65B

GBU-15

LASER

Designator

LANTIRN

PAVE SPIKE

PAVE TACK

GROUND LASER LOCATOR DESIGNATOR (GLLD)

MODULAR UNIVERSAL LASER EQUIPMENT (MULE)/LASER TARGET DESIGNATOR (LTD)

GROUND/VEHICULAR LASER LOCATOR DESIGNATOR (G/VLLD)

Receiver

PAVEWAY II

PAVE PENNY

PAVEWAY III (LIGB/GBU-24B)

Ranger

LANTIRN

PAVE SPIKE

PAVE TACK

(List current as of January 1990)